Performance of the GPS WindEx Real-time Wind Speed Retrieval System during the 2004 Hurricane Season

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Abstract— **This paper reports results from the first tropical storm season's operation of the NASA-Langley's WindEx system. These results are derived from the first quasi-operational deployment of the GPS surface reflection system, a completely new remote sensing technique which has been supported almost from its inception (TRL 2) to its current field evaluation test level (TRL 6) through ESTO funding. WindEx is installed and has been flying on NOAA-AOC's Gulfstream-IV (N49RF, "Gonzo") since June 2004. The WindEx system consists of a GPS reflection system coupled to an integrated, Linux-based, real time processor-network server. The network server hosts a real-time implementation of wind speed retrieval software developed at NASA-Langley, coupled to a moving map display whose coordinate information also is derived from the GPS system. Users on board the Gulfstream IV can open windows at their workstations and receive the moving map with wind speed indicated along with any land features. Hurricanes Bonnie, Charley, and Ivan provided the first operational dropsonde data that could be used in a comparative assessment of WindEx with surface truth. The dropsondes might be called the "gold-standard" for Hurricane Hunters since they are the most relied upon source of surface truth wind speeds. Results are presented demonstrating the very good comparative performance of the WindEx system, while some anomalies are presented and the source of the anomalies with implications to the future are discussed.**

I. INTRODUCTION

The 2004 tropical storm season was an unusually active one with several hurricanes and tropical storms striking the coast of the United States. This active season provided the first opportunity to evaluate the WindEx system developed under with support of the ESTO technology development program. Installed on NOAA's Gulfstream 4 (N49RF, "Gonzo") in mid-2004, the WindEx system consists of one of Langley's GPS surface reflection systems coupled to a real-time wind speed retrieval processor. The processor is connected to the Gulfstream 4, (G-4), onboard data network and hosts server software to make available a moving map display with surface wind speeds to aircraft network clients.

Figure 1-NOAA Gulfstream 4 (N49RF) "Gonzo"

One of the NASA objectives for installing the system on the G-4 was to establish calibration factors for the retrieval algorithms for the high speed Doppler environment of the G-4. Typical flight conditions for turboprop aircraft such as P-3's and King Air's and piston aircraft do not generate significant Doppler shift in the data that must be compensated.

Dropsondes are deployed at locations scattered along the flight path while the GPS technique can produce effectively continuous wind speed retrievals along the aircraft ground track. From the NOAA perspective, a quasi-operational performance evaluation is required to establish the utility for the WindEx system in augmenting dropsonde data, currently the main wind speed sensing methodology on the G-4.

This paper presents results from the 2004 flights circumnavigating some of the tropical storms which occurred summer and fall of 2004. A brief description of the basic GPS technique will be given, the retrieval approach described, which has been found compatible with real time wind speed retrieval, and the real time hardware will be described. Results of comparison of the real time output from the system will be given and compared with data from dropsondes to illustrate system performance.

II. BACKGROUND

The possibility of using GPS reflected signals to infer surface wind speeds was predicted and demonstrated at

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NASA-Langley Research Center beginning with the basic theory [Katzberg and Garrison 1996 and Lin, Katzberg, *et al.*, 1998] and continuing through vigorous flight campaigns between 1997 and 2004. During that time a retrieval approach was developed that permits real time wind speed retrievals utilizing common PC technology [Katzberg and Garrison, 2000].

The GPS technique consists of detecting the electromagnetic signal transmitted by the GPS satellites which reflects off the earth's surface. The reflection of the GPS signals is affected by various surface characteristics such as dielectric constant, conductivity, roughness, etc. Roughness of the surface manifests itself by making the reflected signal a summation of random phasors. The shortest distance to the reflecting surface occurs at the "specular point," i.e., the point that satisfies the geometric optics ray path from GPS satellite to local surface tangent plane to receiving antenna. This is illustrated in Figure 2, where the incoming path from the GPS satellite intersects the x-axis on its way to the receiving antenna. Other paths or "rays" can reach the antenna from surface features whose surface normal causes the reflection of the GPS signal to be towards the antenna. These locations can easily be shown to yield a greater distance (and hence time delay) than that of the specular point.

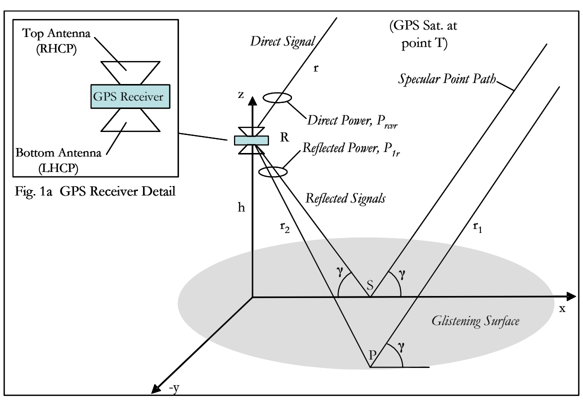

Figure 2-Illustration of the geometry for GPS surface reflection. The point at which the incoming ray strikes the x-axis denotes the "specular point to the local tangent plane. Away from the x-axis, rays can still be redirected to the antenna, but with greater path length compared to that of the specular point.

It can also be readily shown [Beckmann and Spizzichino, 1963] that the loci of areas on the surface that can contribute reflected signals are contained in ellipses of nearly concentric origin and equal excess delay compared to that of the specular point. If scattering surface elements of the correct surface normal exist in these ellipses, they can contribute a component of (randomly phased) signal which superposes to form the total signal power within that delay ellipse. The probability that these scattering surfaces exist with the proper orientation can be shown to be directly related to the surface slope probability density function [Beckmann and Spizzichino, 1963.]

Within the GPS receiver, the detection process consists of cross-correlating the down-converted RF signal with copies of the pseudo-noise codes (PRN's) being transmitted by the satellites. These codes are very nearly orthogonal to one another. Acquisition of these signals consists of sweeping the delay of the reference PRN until a strong correlation (in power of voltage) is detected. The PRN correlation is not perfectly narrow, and for the civilian code (CA) has a width of approximately 1.96 microseconds or 600 meters of delay. Depending on the receiver altitude over the surface, the ellipses of constant delay will have various widths, increasing with greater delay, but each having subtending the same area when projected onto the earth's surface.

Filling of the ellipses comes from the ocean surface developing waves under the influence of surface winds. The ocean surface slopes increase with increasing wind speed but take longer and longer for the winds associated with high wind speed to come to steady state. Nevertheless, experience has shown that the slope probability density developed by Cox and Munk well represents sea surface slopes.

The effect of increasing wind speed on the internal cross-correlation function is illustrated in figure 3. Here, the 0.5 m/s curve represents the correlation function that would be observed from a virtually undisturbed sea surface. As the reference PRN is move against the reflected signal, a perfect match occurs at 1.00 code chip shift and becomes zero over a ±1.00 code chip shift. As the wind speed increases, the ideal correlation spreads to the right (increasing delay) and the shape changes. The shape at any wind speed represents a convolution of the surface slope probability density and the ideal correlation function.

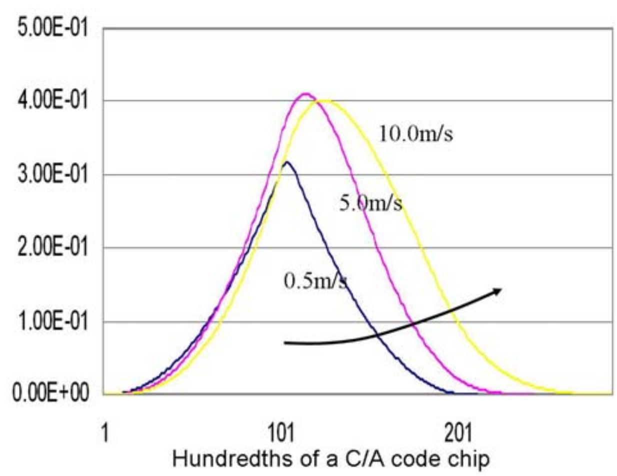

Figure 3-Illustration of the effect of increasing wind speed on the internal correlation function in a GPS receiver.

II. System Description

A. Matched Filter Technique

It is well-known from signal theory that the maximum response from a linear filter occurs if the signal is fed through a filter whose impulse response is a time-reversed copy of the input waveform [Carlson, 1968]. In the ideal case, the signal is contaminated by uncorrelated noise. For the GPS receiver case the "as-transmitted" signal power spectral density at the earth's surface is below the additive thermal noise from the receiver front-end. With a stable GPS transmitted power, the conditions exist for matched filter techniques. When the transmitted signal encounters the rough water surface, an additional noise is developed from the random phase shifts for each individual wave facet or surface area. The signal takes on the characteristics of "fading noise" with the "noise" coming from the signal itself as well as from thermal sources.

As discussed in Carlson, it can be shown that producing the peak signal-to-r.m.s. noise ratio comes from a system whose impulse response is a time-reversed replica of the input signal. The effect of time reversal converts the convolution to a cross-correlation. In the case here this is equivalent is sliding copies of all the possible waveforms against the experimental signal samples for any given altitude and elevation angle for the satellite producing the reflected signal.

B. Hardware and Software Application

The WindEx instrument consists of a GPS reflection receiver and a wind speed server processor. The server receives the GPS reflection data produced by the receiver, performs processing to estimate the surface wind speed, then makes the wind speed data available as a moving map display to requesting client processors on the aircraft network. The client processors are existing systems used by the individual hurricane research personnel. They can be configured to be WindEx clients by downloading the Java client application from the WindEx server via the aircraft Ethernet network, and running that application along with the other applications that the researcher requires. The client application provides a graphical display of a moving map that shows the aircraft position along with the position of the reflection point from the surface of the ocean where the wind speed is being estimated, and any coastlines within the field of view. Information associated with the reflection point includes the estimated wind speed, and a confidence factor that gives the researcher an idea of how reliable the wind speed measurement is. Figure 4 shows a block diagram of the connections between the parts of the WindEx system. The GPS Surface Reflection Instrument (GSRI) receiver receives GPS signals from a zenith viewing RHCP antenna for the direct signals from the satellites and from a nadir viewing LHCP antenna for the reflected signals. The reflected signal data consists of the power versus delay for a range of delay bins encompassing the delay associated with the reflection specular point. This data along with parametric information such as the satellite identifier, the specular point position, and the time is sent via a serial port connection to the Wind Speed Retrieval (WSR) process which runs in the server processor. When the WSR receives the data sent by the GSRI, it performs the matched filter computations necessary to estimate the associated wind speed as well as a confidence estimate for it. The wind speed information, confidence, position, time, and GSRI health signals are then sent to the Moving Map Display Server process which uses it to generate parameters necessary for producing the moving map display. The server process manages all of these parameters along with the moving map imagery and sends it to requesting WindEx client processes that are started by users at other workstations on the ethernet network. When a user starts a Moving Map Display Client process, his workstation makes a request to the server for initialization of the display, which is supplied by the server based on the current parameter set at the time of the request. After the client process sets up the map window and draws the initial map, it begins polling the server for wind speed map data points which are then sent by the server as soon as they are available. WindEx also produces processed retrieval data logs for monitoring and ease of later comparison with dropsondes.

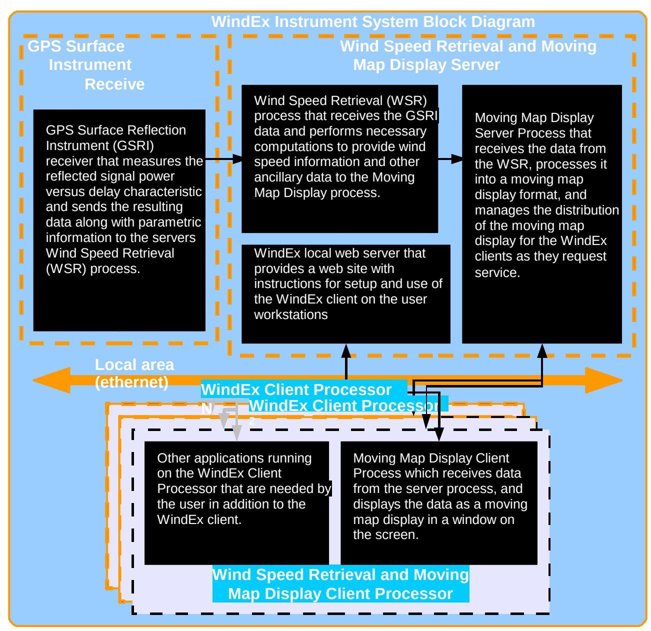

Figure 4-Block diagram of on-board wind speed retrieval system.

III. Results

Data from three 2004 tropical cyclones were acquired: Tropical Storm Bonnie, Hurricane Charley and Hurricane Ivan. Comparisons have been done of the data logs from the WindEx wind speed retrievals and the NOAA "TEMPDROP" files. These files contain the first-look data sets from the G-4 dropsondes. Since only a certain number can be deployed along the aircraft flight path while the GPs operates essentially continuously, subsets of the GPS data were used: The reported dropsonde deployment location along the flight path was used as a center with data averaged within a box of size ±0.1 degrees in latitude and longitude along the path.

Ten figures are attached: The first is a composite of all dropsonde deployments followed by Tropical storm Bonnie (Figure 7) Hurricane Charley (Figure 8) and a group of figures for Ivan (Figures 9-13.) The displayed data is has been edited to remove a small amount that is either missing dropsonde surface level data or has no valid retrieval from the GPS (typically arising from insufficient satellites to give a position fix during aircraft turns.) Also, the data are in order, Bonnie first (all dropsondes) then Charley (all dropsondes) and finally Ivan. Note that in Figure 5, the Bonnie and Charley dropsonde/GPS comparisons are the first 15 plus 41 the succeeding ones are for Ivan.

The large number of deployments for Ivan is representative of Ivan's long life as it crossed and then re-crossed the Florida peninsula, leaving a double dose of devastation. In the figures, the green circles are dropsonde data and the red ones are GPS. The x-axis is dropsonde deployment event, while the y-axis in meters per second. (Multiply this number by 2 to get a close idea of wind speed in knots.)

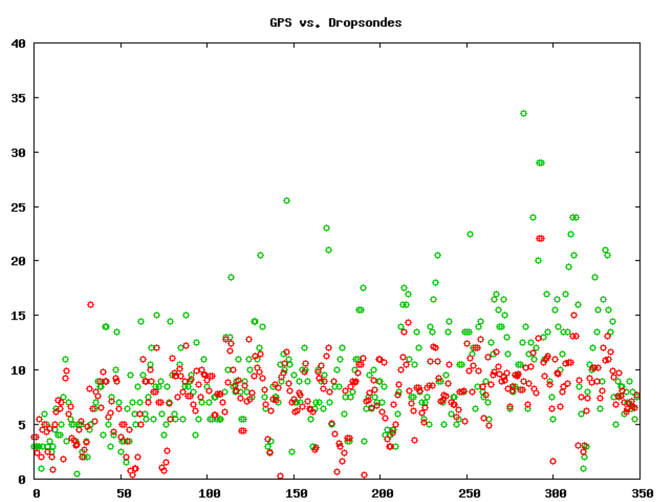

Figure 5-All valid surface dropsonde winds (green) versus GPS valid surface measurements (red) in meters per second. Bulk of data points are from Hurricane Ivan.

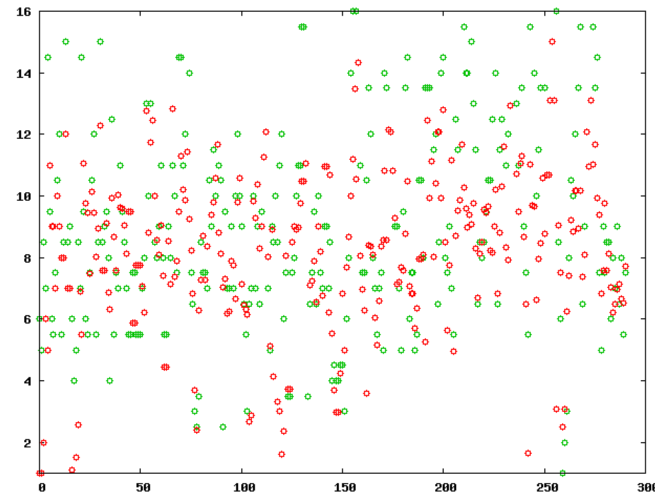

Figure 6 Hurricane Ivan.

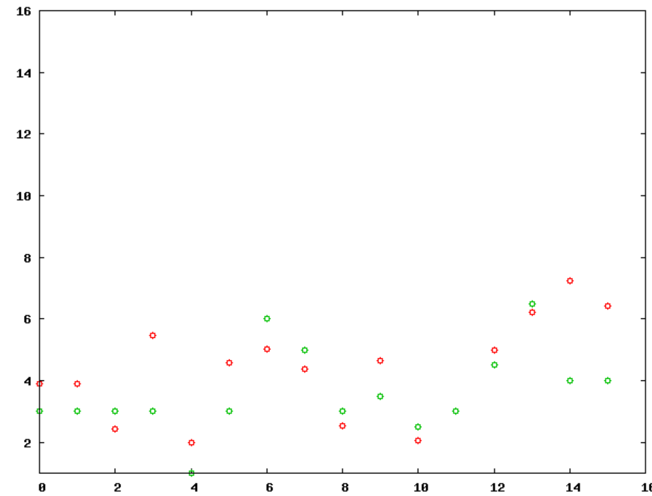

Figure 7 Tropical Storm Bonnie, all dropsondes

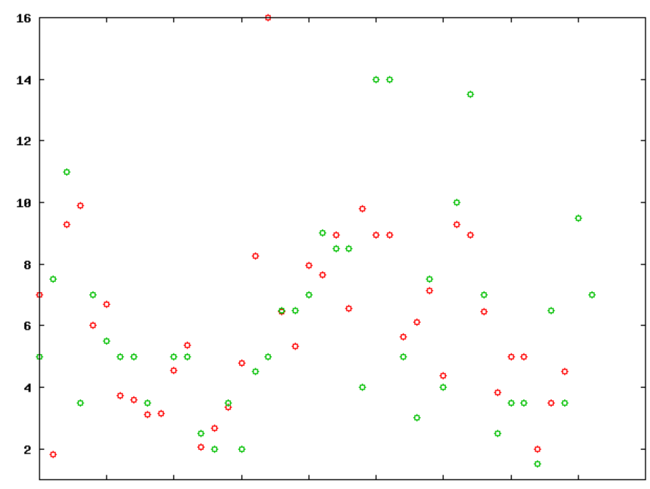

Figure 8-Hurricane Charley, all dropsondes

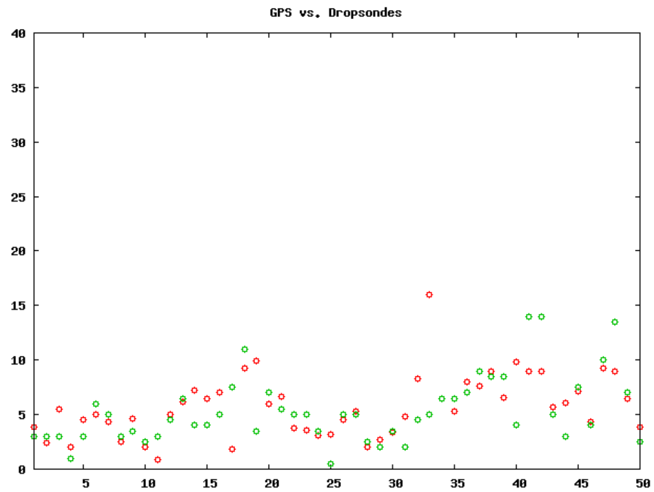

Figure 9-Hurricane Ivan, first 50 dropsonde deployments

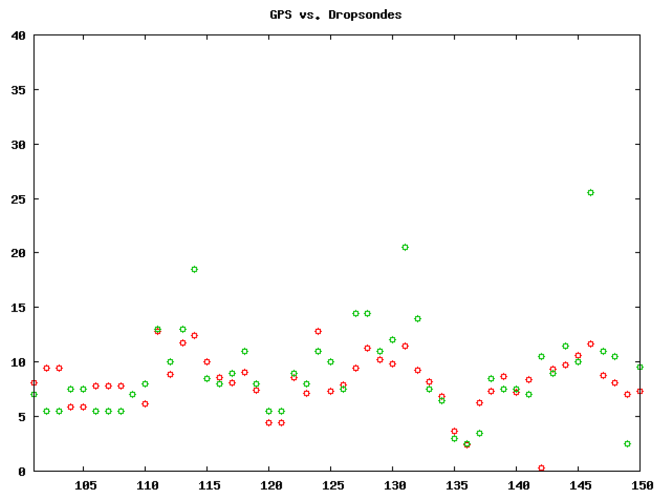

Figure 10- Hurricane Ivan, second fifty

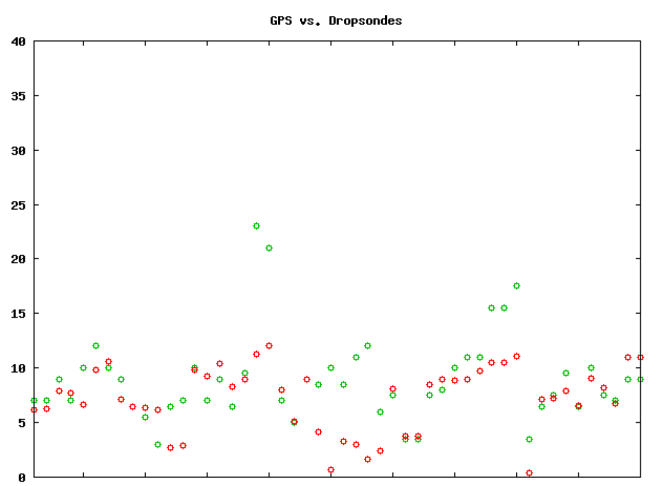

Figure 11- Hurricane Ivan, third fifty dropsonde deployments.

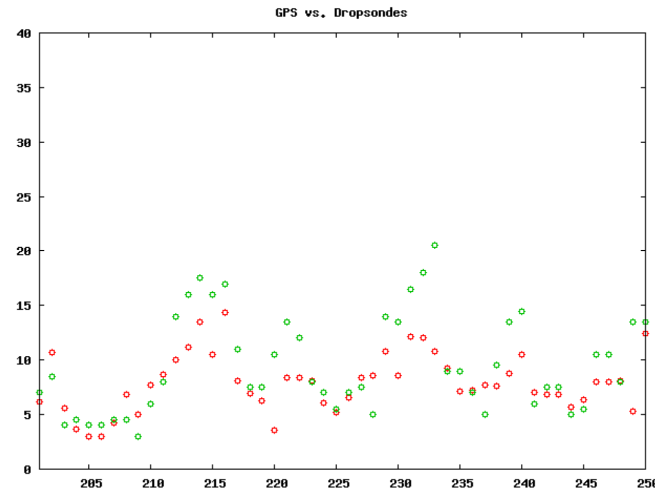

Figure 12- Hurricane Ivan, forth set of fifty.

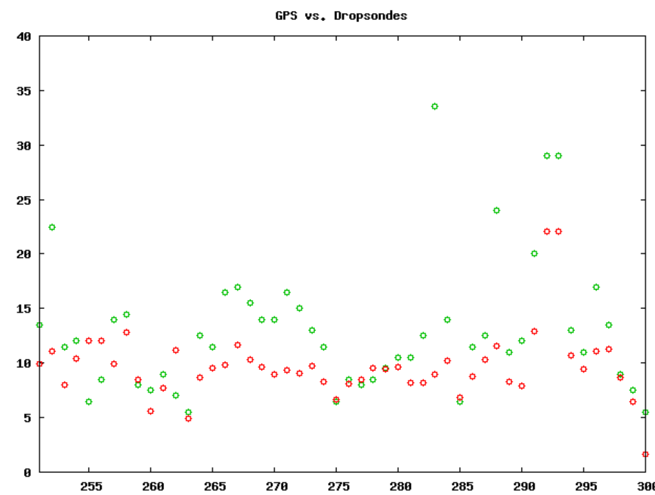

Figure 13- Hurricane Ivan, sixth set of fifty

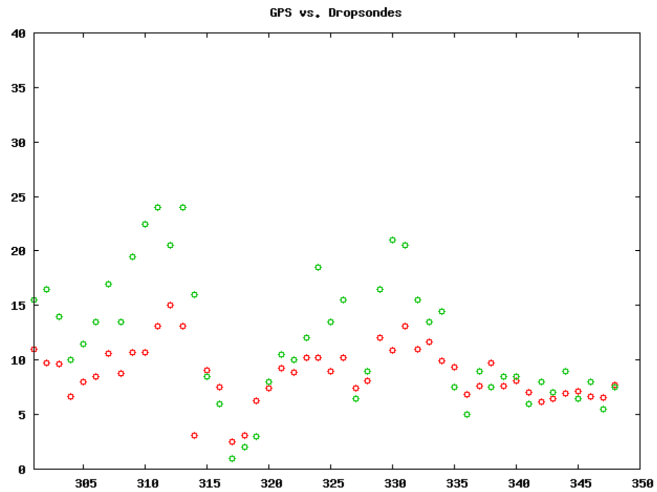

Figure 14- Hurricane Ivan, last set of fifty.

The relatively small number of dropsonde deployments for Bonnie and Charley provides an opportunity to examine detail in the GPS versus dropsonde data.

IV. Discussion

In general the agreement appears to be good for all the storms, with perhaps a slightly lower GPS wind speed compared to the dropsonde reports. There is a certain amount of "pirouetting" between the two for some of the data with the GPS data higher than the dropsonde value and vice-versa. The GPS retrievals do not reach the highest values for the dropsondes, particularly for Ivan.

These slightly lower values may come from Gulfstream IV-induced Doppler effects (reduces the sensitivity in the outer, high wind range bins) or is a result of not-fully-developed sea state (not fully developed slope probability function.) The pirouetting, on the other hand, is believed to be the result of wind direction anisotropy. Essentially, the wind-induced slopes are different cross-wind versus up-wind-down-wind and likely different up-wind versus downwind. At other than normal incidence for the GPS signal, there is a preferential sensitivity to slope probability density along the direction to the GPS satellite versus orthogonal to that direction. The wind direction would affect the overlaying of the slope probability density (azimuthally dependent) onto the preferential sensitivity of the ellipses of constant delay in generating the final signal value. Multiple satellite tracking would be required for this to happen, which is routinely demonstrated.

Proof of, and quantification of, this anisotropy is expected to be the basis of adding wind direction to the retrievals. The WindEx would then be able to provide a wind field moving-map-display of surface wind speed and direction.

V. Conclusions

The first deployment of a real-time wind speed retrieval system based on GPS reflection has been accomplished. Comparisons of data taken during last year's tropical storm season in the U.S. have been presented. It has been demonstrated that the GPS-based technique easily produces wind speed retrievals when flown at a high altitude and high airspeed and that the data generally agrees well with dropsonde deployments. Moreover, some of the disagreement is believed to come from wind direction anisotropy, offering the possibility of complete wind field moving map displays. Finally, since the GPS technique is inherently low impact and the real time retrieval component could be implemented via a wireless RF network, the system presented here could easily be extended to UAV's operating remotely.

VI. References

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